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Tamarixia radiata global distribution to current and future climate using the climate change experiment (CLIMEX) model

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The phloem-limited bacteria, "*Candidatus* Liberibacter asiaticus" and "*Ca*. L. americanus", are the causal pathogens responsible for Huanglongbing (HLB). The Asian citrus psyllid *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) is the principal vector of these "*Ca*. Liberibacter" species. Though *Tamarixia radiata* Waterston (Hymenoptera: Eulophidae) has been useful in biological control programmes against *D. citri*, information on its global distribution remains vague. Using the Climate Change Experiment (CLIMEX) model, the potential global distribution of *T. radiata* under the 2050s, 2070s, and 2090s for Special Report on Emissions Scenarios A1B and A2 was defined globally. The results showed that habitat suitability for *T. radiata* covered Africa, Asia, Europe, Oceania, and the Americas. The model predicted climate suitable areas for *T. radiata* beyond its presently known native and non-native areas. The new locations predicted to have habitat suitability for *T. radiata* included parts of Europe and Oceania. Under the different climate change scenarios, the model predicted contraction of high habitat suitability (EI > 30) for *T. radiata* from the 2050s to the 2090s. Nevertheless, the distribution maps created using the CLIMEX model may be helpful in the search for and release of *T. radiata* in new regions.

Climate change affects biodiversity conservation, food security and economies by inducing extreme weather conditions such as droughts and floods[1,2]. These environmental modifications often lead to changes in global eco-systems, like rising sea levels and reducing suitable areas for crop production and pest outbreaks[3,4]. In response, several studies have assessed climate change impacts on pests and diseases of many crops[5–9]. The findings from such studies provide a theoretical basis for determining species' habitats and generating information that can guide management decisions[10]. Knowledge about climate change impacts on natural enemies of agricultural pests is paramount to integrated pest management strategies. However, information on this is often neglected, necessitating such climate-based simulation studies to develop biological control programs against invasive pests like the Asian citrus psyllid *Diaphorina citri* Kuwayama (Hemiptera: Liviidae).

D. citri is a damaging sap-sucking invasive insect pest of citrus species worldwide. The psyllid is believed to be native to the area between Southeastern and Southwestern Asia, now Pakistan[11]. It directly secretes honeydew and thread-like waxy substances when it feeds on young leaves and stems, leading to new shoots burning or leaves twisting as they mature. Moreover, *D. citri* vectors "*Candidatus* Liberibacter species", which have been implicated in causing Huanglongbing (HLB)[12]. HLB is the world's most deadly disease of citrus species because

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of its ability to decimate citrus trees, reduce fruit production and quality, and shorten the citrus lifespan from about 50 to less than 10 years[13–15].

The economic impact of HLB on citriculture studied from 2007 to 2011 in Florida is well documented revealing estimated losses of about $1 billion and 5,000 jobs yearly[13]. Spreen et al.[16] also reported that financial losses associated with citrus greening in the USA were $3.6 billion with more than 8,000 jobs lost. The long-term damage caused by HLB to the citrus industry in four East African countries has been estimated to be $127 million in Africa[17].

Currently, HLB remains incurable in infected citrus trees in commercial orchards, despite extensive research to find a cure. Some management strategies for vector control and HLB treatment include chemotherapy[18,19], judicious use of pesticides[20], biological control programs[21], and destruction of heavily diseased citrus trees[22,23]. In addition, researchers are investigating the application of gene editing to curb HLB. However, this strategy is challenged by biological and economic setbacks due to the high development cost and requirement of a long period to achieve success. Furthermore, Vázquez-García et al.[24] and Naeem et al.[25] on resistance in *D. citri* strains suggest that an environmentally sound approach is needed to reverse this threat posed by *D. citri* in citrus orchards.

D. citri occurs in the Americas, Asia, Africa, the Saudi Arabian Peninsula and some islands in the Indian Ocean[23]. *D. citri* has the potential to spread to new citrus regions that were initially free of its occurrence[5]. It is possible that *D. citri* spreads naturally from a neighbouring location, where it is already a pest, or brought in by a commodity, transit vector, or a combination of these mechanisms[26]. Nevertheless, the primary route of invasion appears to occur through human-mediated pathways of infested plant materials[17,23], which may explain its recent invasion in East Africa and, more recently in Nigeria in West Africa[27]. *Tamarixia radiata* Waterston (Hymenoptera: Eulophidae) is the most effective parasitic hymenopteran wasp on *D. citri*[23]. It was initially reported as a nymph parasitoid of *D. citri* in China's Fujian province[28]. *T. radiata* can significantly parasitize up to 100% of field populations of *D. citri*, mainly because a single *T. radiata* female can parasitize about 500 nymphs of *D. citri* in its lifetime[29]. As a result, it has been useful in biological control programs against *D. citri* in the USA, China, Brazil, Reunion Island, Taiwan and Guadeloupe[30–32]. Despite *T. radiata*'s effectiveness against *D. citri*, its parasitism varies across different regions due to environmental conditions of geographical areas because climatic conditions affect the fitness parameters of *T. radiata*[33,34]. Given the effects of temperature on parasitoid development, longevity, reproductive output, and mortality[33–35], it is possible that climate change may also affect the ecological range and population growth of the parasitoid[36].

However, several studies on *T. radiata* have mainly focused on its ecology, biology and management[31,37,38], with limited information on how climate change impacts *T. radiata* geographical distribution under climate change. Given that earlier studies have predicted the potential expansion of suitable areas for its main host (*D. citri*) and citrus greening[5,39], it was imperative to study the habitats of *T. radiata* to guide biological control decisions.

Ecological niche modelling (ENM), a widely used technique for identifying areas suitable for species establishment based on environmental limitations employs different modeling methods to map suitable areas of a species[40]. The models are classified into correlative (e.g., Maximum Entropy: MaxEnt) and mechanistic techniques (Climate Change Experiment: CLIMEX)[9,41]. The latter applies physiological stress factors of a species to predict its geographical distribution[42].

The CLIMEX modelling tool helps users to understand the environmental conditions that support the growth or restrict the survival of a species[43,44]. The model has an added benefit of showing which variables other than climate, such as biotic interactions, limit the species' global geographical distribution. The CLIMEX model also helps to provide insight into a climatic response of a species, which can be obtained through observations of its distribution range, phenology, and laboratory studies[45]. The parameters for the model are derived from temperature, moisture and day length. In this study, CLIMEX software (version 4.0, Hearne software, Australia) was utilized to predict the potential distribution of *T. radiata* under 2050, 2070 and 2090, for the Special Report on Emissions Scenarios (SRES) A1B and A2[45,46].

Material and methods

The modeling process was divided into four stages: (i) collection of distribution points, (ii) preparation of bioclimatic and elevation datasets, (iii) CLIMEX modeling, and (iv) development of *T. radiata* habitat suitability maps. The technical flow chart of our study is illustrated in Fig. 1.

***Tamarixia radiata* historical records.** *Tamarixia radiata* occurrence was obtained by collecting information and geographic coordinates contained in online databases: Global Biodiversity Information Facility (GBIF, https://www.gbif.org/species/1388189), Center for Agriculture and Biosciences International (CABI, https://www.cabi.org/isc/datasheet/53427), and through published bibliography[21,31,33,34,38,47–58]. Afterwards, we verified and analyzed 335 occurrence points distributed in the continents of America, Africa, and Asia (Fig. 2).

CLIMEX model. CLIMEX software (version 4.0.0, Hearne software, Australia) is specialized in predicting the potential distribution of a species through its biological and climatic variables[45,59,60]. In this study, we defined the physiological stress factors of *T. radiata* from biological information of the insect and climatic conditions of the places of occurrence[47,53,55,60–65].

CLIMEX provides the ecoclimatic index (EI), which is described on a scale from 0 to 100, where 0 indicates areas unsuitable for the occurrence and 100 indicates areas with high suitability for the occurrence of the species[45]. The EI is calculated based on the Growth Index (GI), Stress Index (SI), and Stress Interaction (SX)[60]. Specifically, we used the IE categories to organise the data for this investigation: EI = 0 (unsuitable), 0 < EI < 30 (low suitability), EI > 30 (high suitability)[66–68].
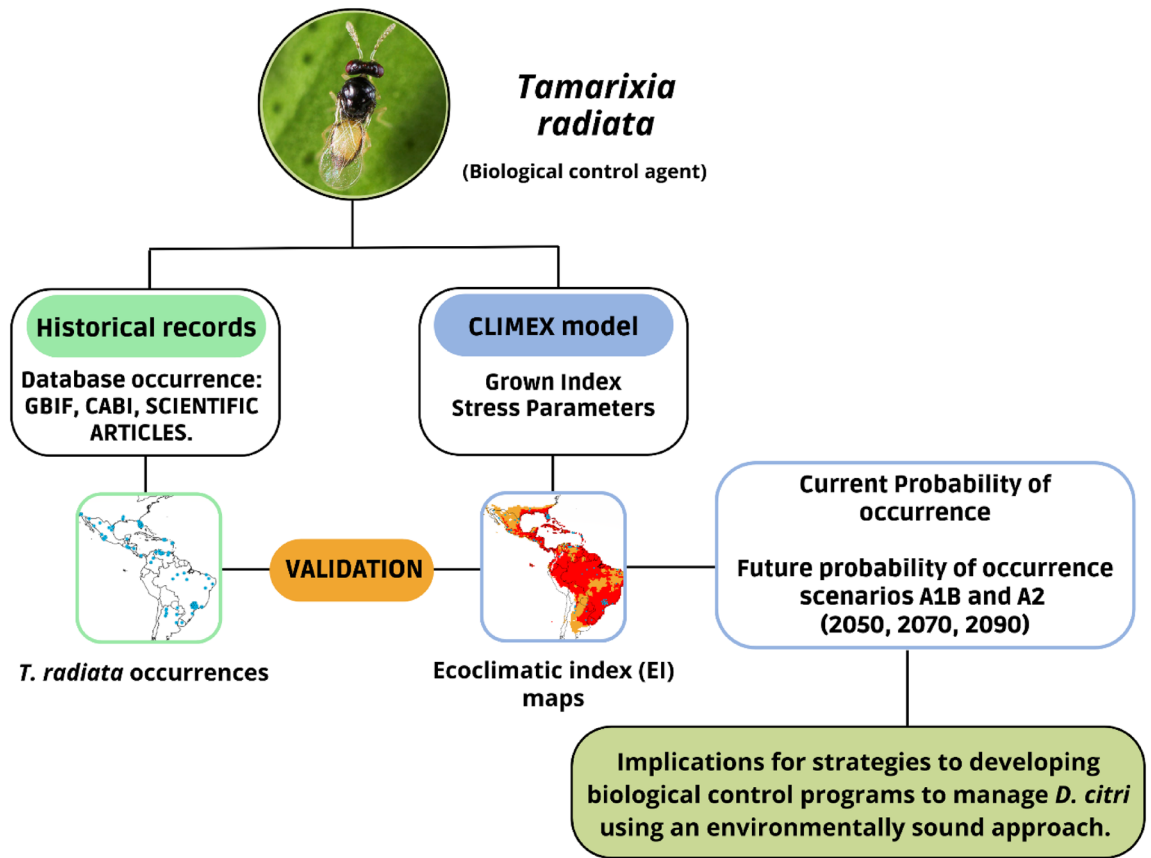
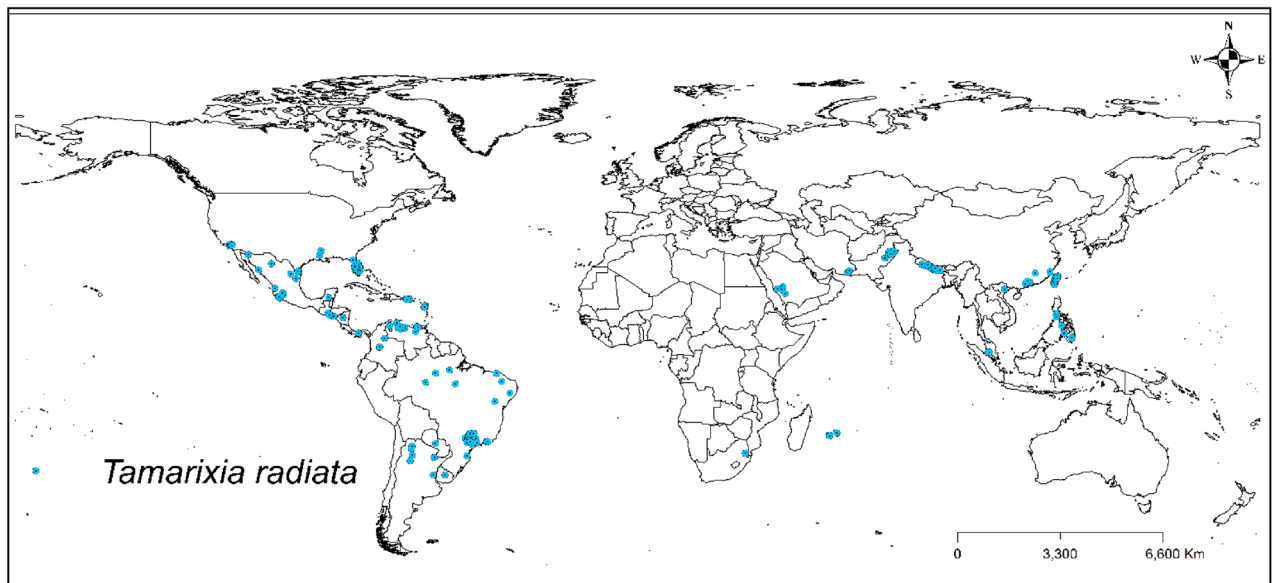**Figure 1.** Technical flow chart of the study.

Figure 2. *Tamarixia radiata* occurrence worldwide. ESRI ArcMap 10.2.2: (https://support.esri.com/en/Products/Desktop/arcgis-desktop/arcmap/10-2-2#downloads).

Climate change scenarios.   In this step, a 10' gridded climate dataset was used to model *T. radiata* for future climate change scenarios in 2050, 2070 and 2090, for the SRES A2 (without mitigation) and A1B (with mitigation) scenarios and the CSIRO global climate model (GCM) -Mk3.0 (CS) from the Center for Climate Research, Australia. CliMond provides 10' high-resolution global data representing long-term values based on average monthly minimum (*Tmin*) and maximum (*Tmax*) temperatures, monthly total precipitation (*Ptotal*)

and 9:00 am relative humidity, and 15:00 h[69]. The Fifth Assessment Report (AR5) published by the Intergovernmental Panel on Climate Change—IPCC presents four updated greenhouse gas trajectories (Representative Concentration Pathways—RCPs) to replace the SRES scenarios. Compared to the current Report scenarios (AR5), the A2 SRES scenario is equivalent to RCP 8.5, as it presents similar forecasts until the end of the century. The A2 SRES scenario predicts an increase in atmospheric concentrations of CO_2 by 846 ppm and an increase in temperature of 6 °C at the end of 2100, while its RCP 8.5 equivalent indicates an increase of 7 °C in Temperature and CO_2 concentrations of 936 ppm[70]. Associated with this, the A2 SRES scenario incorporates representative data on technology, demographics, and economic variables related to greenhouse gases (GHG) from independent and self-sufficient countries, which gives it proven consistency in its assumptions[67].

Parameters used in CLIMEX. *Moisture parameters.* In CLIMEX, the moisture content is established by four parameters, being the lower limit of soil moisture (SM0), the optimal lower soil moisture (SM1), the optimal moisture of the upper soil (SM2), and the upper limit of soil moisture (SM3)[71]. We determined the lower soil moisture threshold (SM0) and the upper soil moisture threshold (SM3) from the best fit of the model in the software and according to the global distribution of *T. radiata*. Also, we used relative humidity to define the lower optimum soil moisture (SM1) and upper optimum soil moisture (SM2), the parametric value provided by the temperate model in CLIMEX and the parametric value provided by the temperate model in CLIMEX[64]. The lower (SM0), ideal (SM1 and SM2), and upper (SM3) limits established were 0.07, 0.8, 1, and 3 (Table 1), respectively.

Temperature parameters. In CLIMEX, temperatures are defined in four parameters, the lower temperature limit (DV0), the lower optimum temperature (DV1), the upper optimum temperature (DV2), and the upper temperature limit (DV3)[60]. Variables DV1 and DV2 represent the most favourable temperature range for the species. The temperature requirements of *T. radiata* have already been reported, so the lower temperature limit (DV0) used in the model was 15 °C because the insect does not emerge below this temperature[55,63]. As for the lower optimum temperature (DV1) and the upper optimum temperature (DV2), they were set at 20°C and 30°C, respectively, these temperatures being ideal for the growth and establishment of *T. radiata*[55,62,65,72]. The upper-temperature limit (DV3) was 35 °C, which has low insect parasitism rates[47,55,63].

Stress parameters. Stresses are characterized by non-ideal environmental conditions that restrict the establishment of a species in a region[71]. In CLIMEX, four types of stress parameters are defined, namely: CS (cold stress), HS (heat stress), DS (drought stress), and WS (moisture stress)[73]. The stress parameters used in our models were cold stress degree day threshold (DTCS), cold stress degree day rate (DHCS), heat stress temperature threshold (TTHS), temperature rate stress threshold (THHS), dry stress threshold (SMDS), dry stress ratio (HDS), wet stress threshold (SMWS) and wet stress ratio (HWS). The values for the stress parameters were established according to the best fit in the software according to the regions of occurrence of *T. radiata* and in the parametric value provided by the Mediterranean and temperate model in CLIMEX (Table 1).

Index	Parameter	Values	References
Temperature	DV0 = lower threshold	12 °C	McCalla et al.[47]
	DV1 = lower optimum Temperature	25 °C	McCalla et al.[47]
	DV2 = upper optimum Temperature	29 °C	McCalla et al.[47]
	DV3 = upper threshold	35 °C	Fauvergue & Quilici [65]; Castillo et al.[63]; Gómez-Torres et al.[55]
Moisture	SM0 = lower soil moisture threshold	0.07	Fit to data
	SM1 = lower optimum soil moisture	0.8	McFarland & Hoy [64]
	SM2 = upper optimum soil moisture	1	Kriticos et al.[60]; Fit to data
	SM3 = upper soil moisture threshold	3	Fit to data
Cold stress	TTCS = temperature threshold	0	–
	TTHS = stress accumulation rate	0	–
	DTCS = degree day threshold	10 °C-days	Ramos Aguila et al.[72]
	DHCS = stress accumulation rate	− 0.001	Kriticos et al.[60]; Fit to data
Heat stress	TTHS = temperature threshold	37 °C	Kriticos et al.[60]
	THHS = stress accumulation rate	0.00001 week^{-1}	Kriticos et al.[60]; Fit to data
Dry stress	SMDS = soil moisture threshold	0.1	Kriticos et al.[60]; Fit to data
	HDS = stress accumulation rate	− 0.01 week^{-1}	Kriticos et al.[60]
Wet stress	SMWS = soil moisture threshold	2.5	Kriticos et al.[60]; Fit to data
	HWS = stress accumulation rate	0.1 week^{-1}	Kriticos et al.[60]; Fit to data
Degree-days	PDD = degree-days	189	Gómez-Torres et al.[54]

Table 1. CLIMEX parameter values used for *Tamarixia radiata* modelling.

Cold stress. The development of insects can be influenced by temperature, as they are ectothermic organisms[74,75]. Low temperatures can affect the development of *T. radiata*, in which there is no oviposition below 10 °C[72]. Therefore, the degree day threshold (DTCS) was set at 10 °C and the stress accumulation rate (DHCS) was set at -0.001 to adjust the insect distribution in the occurrence areas.

Heat stress. Oviposition and development of *T. radiata* are not possible at temperatures above 35 °C[72,76]. Moreover, *T. radiata* exposed to heat treatment (38 °C) for 15 min survived[77]. However, when the heat stress was maintained for 2 h, about 65% of *T. radiata* died. Thus, we considered the 37 °C temperature threshold (TTHS) to be the best fit of the model outputs to the areas of *T. radiata* and stress accumulation rate (THHS) at 0.00001 week^{-1} (Table 1).

Dry stress. Considering the regions of occurrence of *T. radiata*, the dry stress threshold (SMDS) was adjusted to 0.1, and the dry stress accumulation rate (HDS) was fixed at -0.01 week^{-1} (Table 1) covering temperate regions.

Wet stress. The parameters of wet stress (SMWS) and stress to the accumulation rate (HWS) were defined based on the CLIMEX parameters for humid tropical regions, which are similar to the insect's distribution regions and the best fit of the output of the insect model. Therefore, SMWS was set to 2.5, and HWS was set to 0.1 week^{-1} (Table 1).

Model validation. We evaluated the CLIMEX model performance based on the distribution of the species, mainly in the regions of America and Asia, where higher occurrences were observed. The verification demonstrates reliability in the final model, and most distribution data are inserted in areas with a high Ecoclimatic Index (Fig. 3).

Human or animal rights. This article does not contain any studies with human participants or animals performed by any of the authors.

Results

Model validation. The distribution of the species, particularly in the parts of America and Asia where higher occurrences were noted, was used to validate the model. In addition, the habitat suitability for *T. radiata* obtained from the model settings in Table 1 covered both native and non-native present distribution points of the parasitoid. This verification demonstrates reliability in the model's predictions, and most of the distribution data were found in areas with high Ecoclimatic Index (Fig. 3).
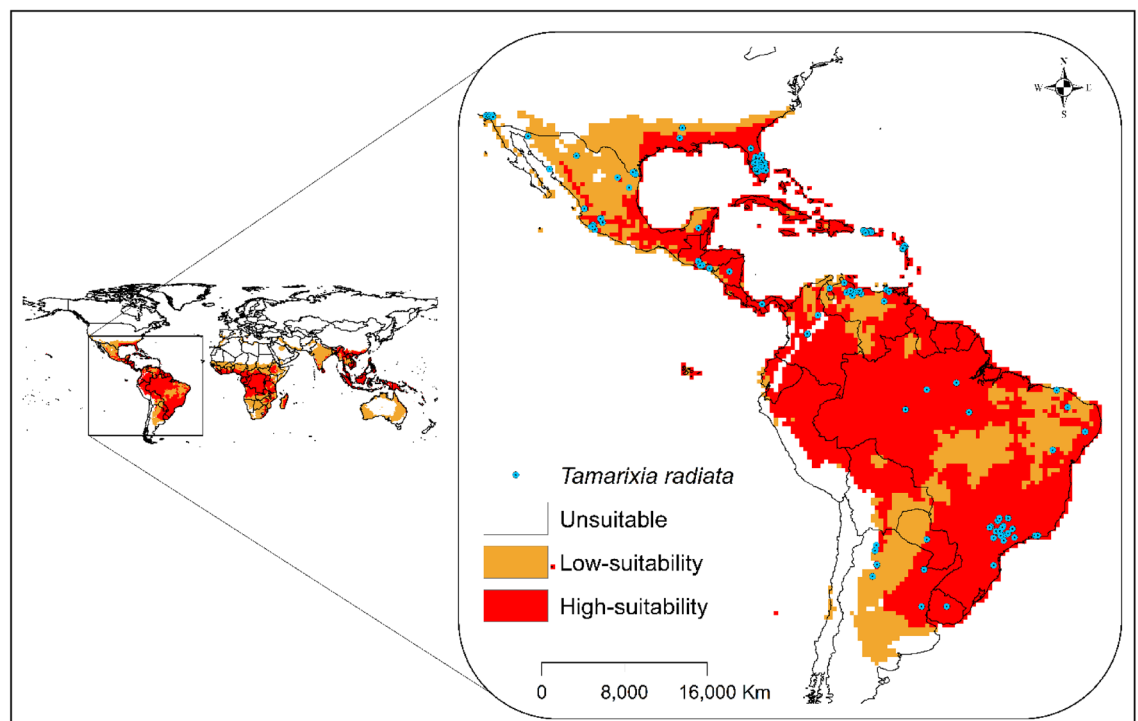

Figure 3. Current and potential distribution of *T. radiata* in the model's validation region, based on the EI index. ESRI ArcMap 10.2.2 (https://support.esri.com/en/Products/Desktop/arcgis-desktop/arcmap/10-2-2#downloads) and CLIMEX 4.0.0 (https://www.hearne.software/Software/CLIMEX-DYMEX/Editions).

Potential global distribution of _T. radiata_.   Under the current time, the model predicts that suitable areas for the establishment of _T. radiata_ are found in the world's tropics and subtropical climates (Fig. 4). The predicted suitable areas exceeded the known distribution points of the parasitoid with high habitat suitability (for EI > 30) covering all continents except Antarctica. The areas with high suitability for _T. radiata_ occur in parts of Brazil, Mexico, and the USA in the Americas; Ghana, Nigeria, Kenya, and South Africa in Africa; China and India; and Australia and Papua New Guinea in Oceania.

In the future scenario (SRES A1B), the potential global distribution of _T. radiata_ shows a contraction in areas that were projected to be optimal in the current climate (Fig. 5). Specifically, the model predicts that low suitability (0 < EI < 30) will increase, while high suitability (EI > 30) for the parasitoid will decrease from the 2050s to 2090s. The model predicts that by 2050, areas in the Americas, Africa, Asia, and Oceania will all be suitable for _T. radiata_. These include parts of Uruguay, Paraguay, Argentina, Brazil, Nicaragua, Cayenne, Guyana, Venezuela, Peru, Colombia, and Honduras. The areas that will continue to have high suitability for _T. radiata_ include parts of Brazil, Paraguay, Uruguay, Argentina, and Nicaragua in the Americas; Tanzania, Uganda, Madagascar, Cameroon, and South Africa in Africa; and China and Indonesia in Asia.

Under the SRES A2 scenario, the results showed that areas highly suitable for the parasitoid would be concentrated mainly in parts of Brazil, Surname, Uruguay, Paraguay, Peru, Argentina, Colombia and the USA in the Americas; Madagascar, Tanzania, South Africa and Kenya in Africa; China and Indonesia in Asia; and Papua New Guinea in Oceania (Fig. 6). The prediction shows contraction of suitable areas from the current time until the 2090s. In the future, areas with high habitat suitability for _T. radiata_ mainly occur in countries, such as Paraguay, Uruguay, Brazil, and Argentina in the Americas; Madagascar, Kenya and Tanzania in Africa; China and Indonesia in Asia; Australia and Papua New Guinea in Oceania; and Italy, Spain, Portugal and Greece in Europe.

Discussion

Natural enemies, such as parasites, predators and parasitoids, are sensitive to temperature changes and may be affected by climate through extrinsic and intrinsic mechanisms[78]. Consequently, global warming is expected to induce a shift in the ecological range of many species, thereby causing habitats that are presently suitable to become unsuitable for their establishment in the future[5]. If pests migrate into areas where their natural enemies are absent, the ability of these biological control agents to keep them in check will reduce. However, a new natural enemy community may help provide some level of control[79]. As the earth warms, natural enemies of herbivores, in particular, may find it difficult to parasitize on their host effectively[80]. Moreover, changes in temperature, humidity, and soil moisture patterns, as influenced by climate change, may have substantial implications on the population and behaviour of natural enemies because farmers are likely to use adaptive management practices to adjust to climate change[79].

In this study, the CLIMEX model was used to define the potential global geographical distribution of _T. radiata_, using the physiological stress factors of the parasitoid. Our predictive results were consistent with the historical distribution records of _T. radiata_. The model's prediction was reliable as assessed by predictive performance in its native and non-native areas. We found that the majority (61.49%) of these historical records fell
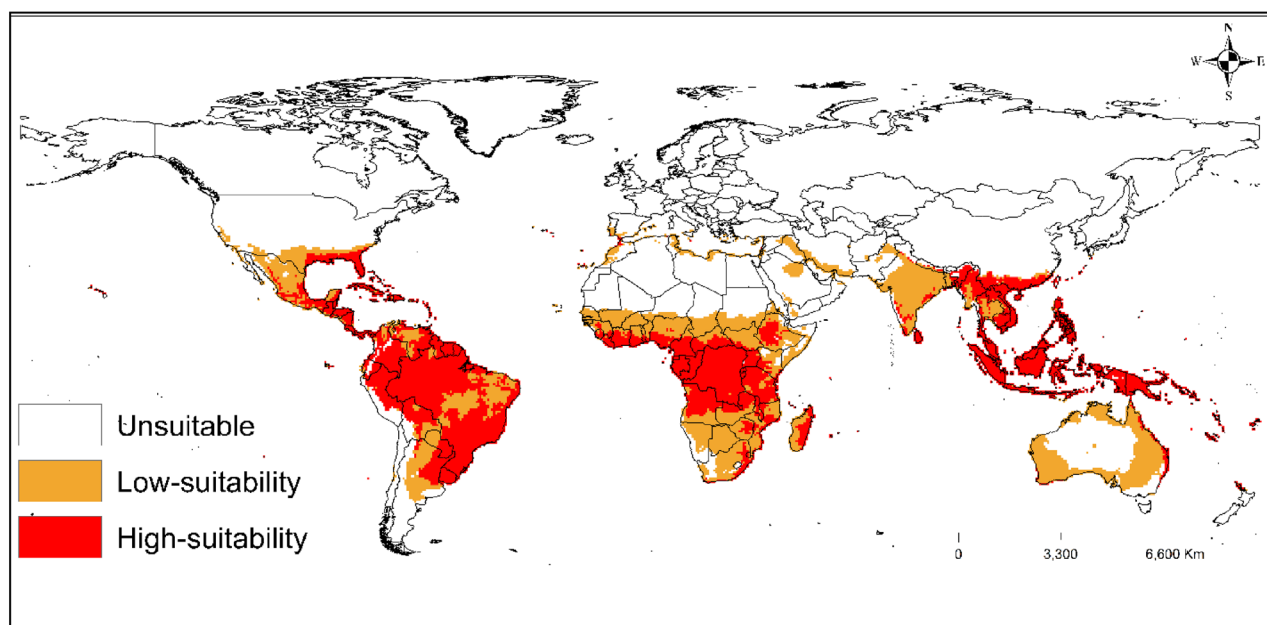

Figure 4. Ecoclimatic index (EI) for the occurrence of _T. radiata_ at the current time, modelled using the CLIMEX model. Inadequate (if EI = 0), low suitability (when 0 < E I < 30), and high suitability (when 30 < EI < 100). ESRI ArcMap 10.2.2 (https://support.esri.com/en/Products/Desktop/arcgis-desktop/arcmap/10-2-2#downloads) and CLIMEX 4.0.0 (https://www.hearne.software/Software/CLIMEX-DYMEX/Editions).
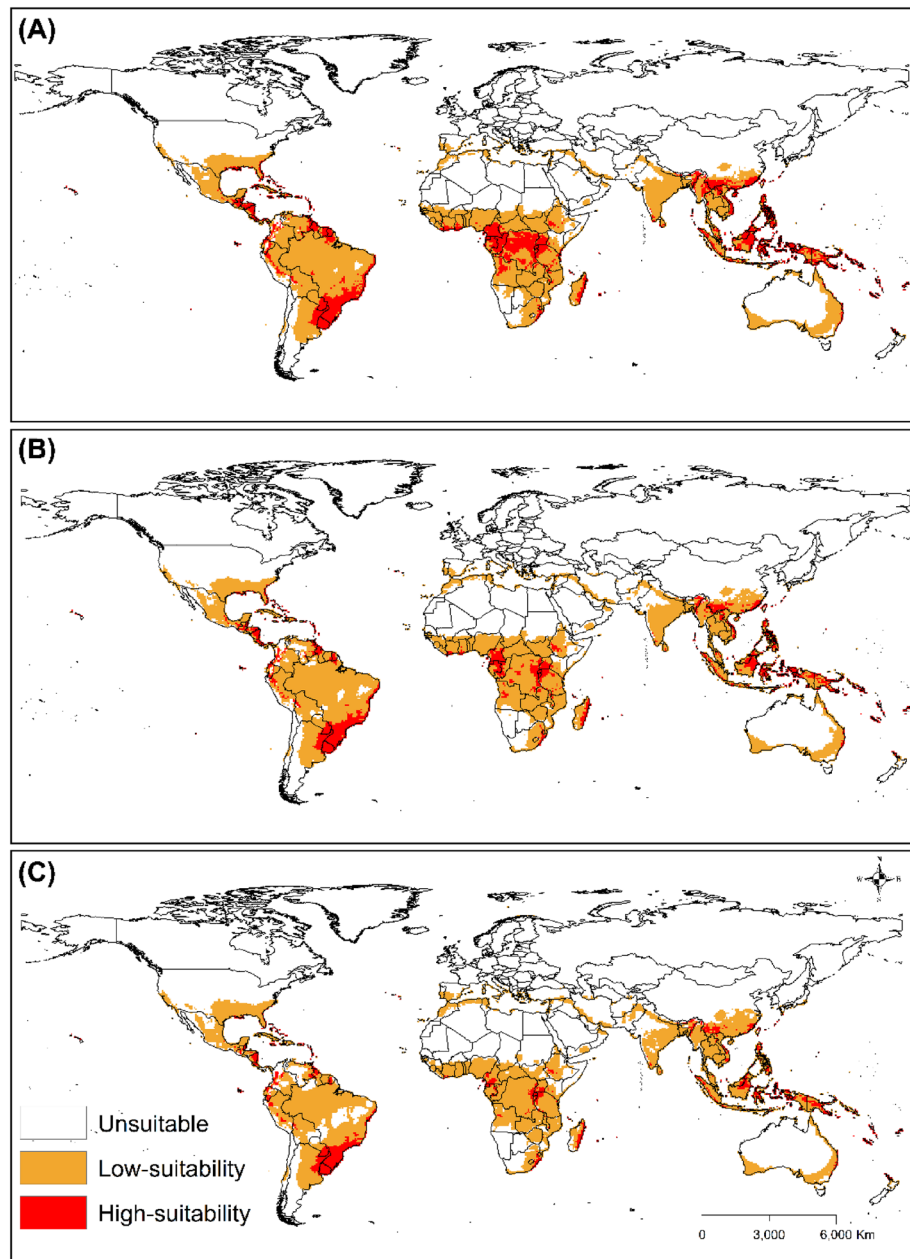
Figure 5. The Ecoclimatic Index (EI) for *T. radiata* modelled using the CLIMEX model in the CSIRO-Mk3.0 GCM running the SRES A1B scenario for 2050 (**A**), 2070 (**B**), and 2090 (**C**). ESRI ArcMap 10.2.2 (https://support.esri.com/en/Products/Desktop/arcgis-desktop/arcmap/10-2-2#downloads) and CLIMEX 4.0.0 (https://www.hearne.software/Software/CLIMEX-DYMEX/Editions).

within the areas predicted to be highly suitable for the parasitoid, followed by 34.63% in areas with low suitability, and then 3.88% of the points occurring in areas of unsuitability. In its native range, low to high EI values of habitat suitability for *T. radiata* were found in most parts of Asia, where it is believed to be the aboriginal home of the parasitoid.[11,23] The areas predicted to be suitable for *T. radiata*, were also predicted to have suitability for *D. citri*.[5]

Despite biotic and abiotic factors considered in the present study, our model predicts that habitat suitability for *T. radiata* could expand outside its presently known native and non-native areas. Specifically, parts of the world that showed expansion of the suitable regions but have not recorded *T. radiata*, include Kenya, Tanzania, Ethiopia, Uganda, and Nigeria in Africa; Australia and Papua New Guinea in Oceania; Thailand and Cambodia in Asia; and Portugal and Spain in Europe. Moreover, our model predicts that large areas in Africa are suitable for the parasitoid, such as Nigeria, Kenya, Nigeria and Tanzania where *D. citri* is present[5,23,27]. Thus, researchers can utilize our maps to create ecologically acceptable management plans against *D. citri* in continents where it is present, such as Asia and the Americas[12].

The CLIMEX model shows that the potential distribution of *T. radiata* is primarily centered within tropical and subtropical climates, with a few habitat suitability in the Mediterranean climates. This habitat suitability
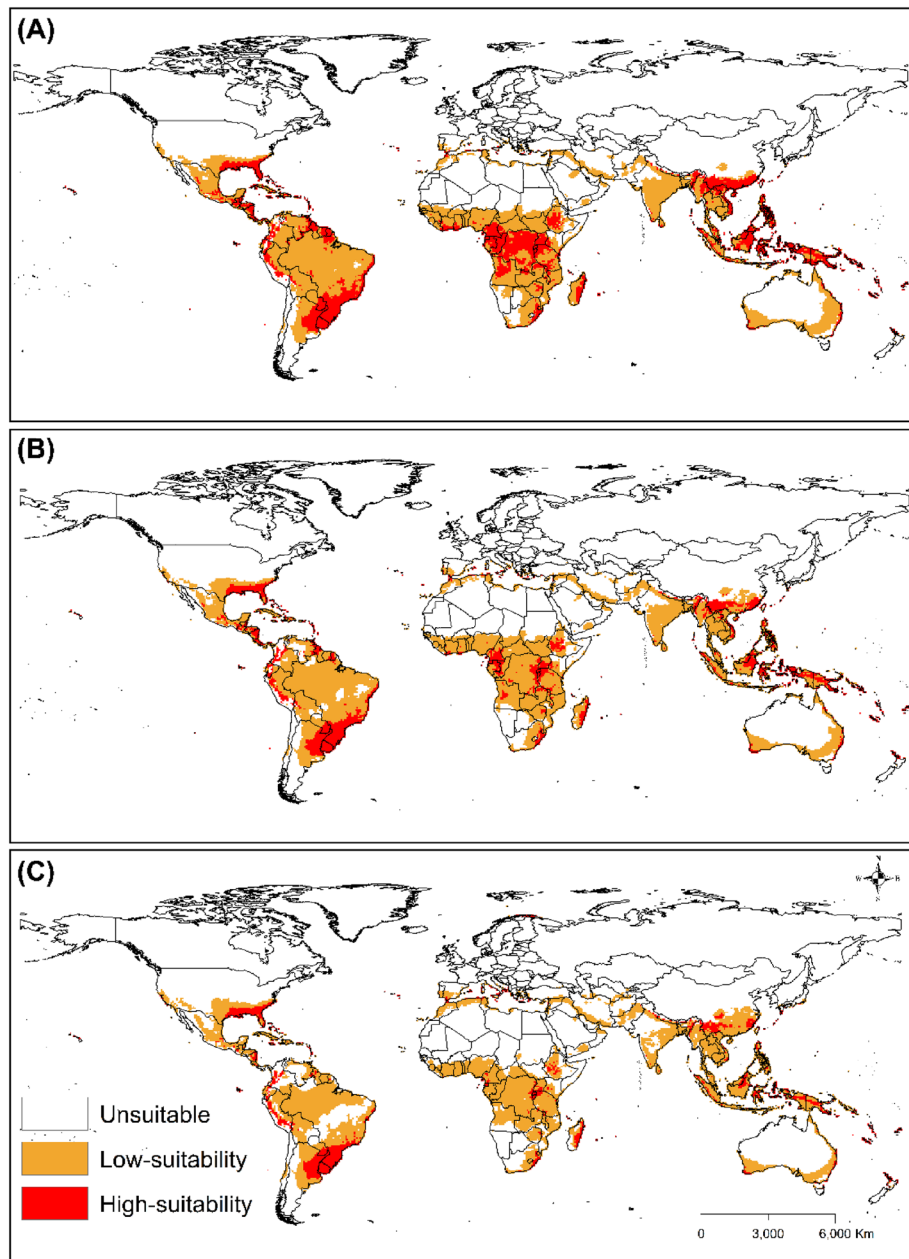
Figure 6. The Ecoclimatic Index (EI) for *T. radiata* modelled using the CLIMEX model in the CSIRO-Mk3.0 GCM running the SRES A2 scenario for 2050 (**A**), 2070 (**B**), and 2090 (**C**). ESRI ArcMap 10.2.2 (https://support.esri.com/en/Products/Desktop/arcgis-desktop/arcmap/10-2-2#downloads) and CLIMEX 4.0.0 (https://www.hearne.software/Software/CLIMEX-DYMEX/Editions).

for *T. radiata* is likely to be widely distributed within tropical climates, with habitat suitability ranging from low to high, probably due to its warm temperatures throughout the year[80]. Within the subtropical climates, areas below the equator showed either low or unsuitability for *T. radiata*. In contrast, the most suitable climate areas within the subtropical climates above the equator ranged from low to high habitat suitability for the *T. radiata*.

The predictions show that the highly suitable areas in Australia are confined to a narrow margin along the eastern and western coasts, with most of the inland areas, south and northern parts of the country having unsuitability to low habitat suitability for *T. radiata*. According to earlier reports[47,54], the establishment of *T. radiata* is likely to occur in areas with warm and dry climates, where temperatures do not exceed the lower and upper thresholds of 12 and 35 °C, respectively, for the development and survival of life stages[47,54,63,65]. Moreover, transcriptome analysis of *T. radiata* showed that heat stress significantly induced the transcription of immunological response, stress signaling transduction, and oxidation resistance, including highly expressed heat shock proteins, ATPases, and detoxifying enzymes[77]. Ramos Aguila et al.[35], found that *T. radiata*'s host-feeding activity is temperature-dependent and varied across temperature regimes: the host-feeding rate increased as the temperature increased up to 30 °C, started decreasing after this temperature, and decreased to its lowest level at 35 °C.

When *T. radiata* was exposed to different temperature regimes, the highest levels of fecundity, net reproduction rate, intrinsic growth rate, and maximum growth rate were observed at 27.5 °C, and population growth was faster at temperatures ranging between 27.5 and 30 °C[36].

In the USA, our modelling results show that *T. radiata* is distributed more narrowly in the country, primarily along the southern coast of the states (i.e., North and South Carolina, Mississippi, Louisiana, New Mexico, Arizona and California). Furthermore, the model predicts that entire states, such as Florida and Texas, are suitable for *T. radiata*. For instance, in Texas, favourable winter weather conditions are warm and dry with occasional frosty nights, followed by suitable summer conditions that are hot and humid, and moderately hot. During summer, the minimum, and maximum temperatures in Florida range from 32 to 35 °C, although mean summer temperatures are above 21 °C in other states across the southern parts of the USA (Florida Automated Weather Network at https://fawn.ifas.ufl.edu).

Under CSIRO-Mk3.0 GCM for the SRES A1B and A2, the model predicts that the suitable global areas for *T. radiata* will decrease from the 2050s to the 2090s. However, some areas, like the northern fringes of Africa, will become more suitable for *T. radiata* in the future. This suggests that future climate change will alter the geographic distribution of *T. radiata* depending on the geographical region. Moreover, global warming will cause some countries within subtropical climates, such as Greece, Italy, and Portugal, to have a marginal expansion of suitable habitats for *T. radiata*. This supports previous studies which demonstrate that climate change will affect the geographical distribution of many species in the future[81–84].

Notwithstanding the validity and reliability of our model predictions, we need to mention that certain limitations or drawbacks should be considered when interpreting any species distribution models. In this study, our CLIMEX employed climate-related factors, meteorological datasets and distribution points of the target species to determine the areas suitable for *T. radiata*. However, several environmental variables, such as elevation, vegetation, human factors, hyperparasitoids, and availability of its host (*D. citri*) may influence the distribution of the parasitoid but were not considered in the present study. Another important factor to be considered in species distribution modelling is the uncertainties associated with future predictions. Achieving these SRES depends on several factors, like the release of atmospheric greenhouse gases. As a result, these uncertainties should be considered when analyzing the results.

Despite these limitations, our modelling outputs are critical for understanding the factors limiting the distribution of *T. radiata* for effective biological control programs. In particular, our suitability maps show the importance of using species' physiological stress factors and occurrence records to define species' ecological niches and improve the performance of modelling outcomes. Our suitability maps can be useful for developing biological control programs because the maps can guide ecologists, biologists, plant protection agencies and pest managers to identify suitable areas for mass rearing and releasing the parasitoid.

Conclusion

The potential distribution of *T. radiata* has been defined globally using the CLIMEX model. The model predicted climate suitable areas outside the present day known distribution regions of the parasitoid. Our model predicted habitat suitability for *T. radiata* in all continents except Antarctica. The new areas identified as suitable for *T. radiata* included parts of Europe and Oceania. Habitat suitability for *T. radiata* will decline from the 2050s to the 2090s under the different climate change scenarios. The distribution maps created using the CLIMEX model may be helpful in the search for and release of *T. radiata* in new habitats. Moreover, our modeling idea can be adopted by other studies to predict the geographical distribution of biological control agents.

Code availability

Please contact the corresponding author for code of decent request.

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Author contributions

P.G.C.S., O.F.A., P.K.B.F., W.K.H., M.C.P., R.S.S., and P.A.S.J. conceived and designed research. O.F.A., W.K.H., P.G.C.S. and R.S.S. wrote the first draft. P.G.C.S., F.K.B., K.D.N., S.A.S., M.A.S. and O.F.A. acquired data. P.G.C.S., R.S.S., P.K.B.F. and O.F.A. analyzed the data. All authors read the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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